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28 September 1993

Dr. Robert Abbey, Scientific Officer
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Dear Dr. Abbey:

Enclosed are three copies of the second annual performance report on ONR Grant No. N00014-92-J-1069. Four other copies have been sent to the other addresses listed in the award notice.

The IOP of COARE occurred during the second year, and the data set is beginning to take shape. John McBride and I have put together a pretty complete data set from the rawinsondes and surface reports, filling in missing data wherever possible. We are very encouraged by the early results, as we have been able to get on with performing the budgets and other analyses described in the proposal. The enclosed report just shows preliminary highlights to give some idea of the types of products that are now starting to be produced, but we hope to be at a stage where we can start writing the first journal article by the first of the year. The TCM90 work is also coming along. The M.S. student working on that data set should finish his thesis by December of this year.

Thank you again for your continued support. I am very encouraged by the early returns from COARE, and I anticipate some very interesting results within a few months.

Best Regards,

William M. Frank

William M. Frank
Professor

ANNUAL REPORT #2

ONR Grant No. N00014-92-J-1069

The Vertical Distribution of Heating in the Tropical Atmosphere

PIs: William M. Frank and John L. McBride
28 SEP 1993

1. Project Goals

The project has three major research goals:

* Assist the planning of TOGA COARE.

* Participate in the TOGA COARE field program.

* Carry out a research program using the TOGA COARE data set to examine the mean properties and vertical heating profiles of mesoscale and larger scale phenomena in the COARE region. The work will focus on exploring relationships between tropical weather systems in this region and larger scale forcing, and determining processes that affect the vertical structure of the tropical atmosphere.

2. First Year Accomplishments

First year work was described in the first annual report. It consisted of participating in planning meetings for COARE, preparing data processing and handling techniques, and developing modelling techniques for use in the simulation studies of the COARE region vertical structure during year three.

3. Second Year Accomplishments

3.1 Planning for and participation in COARE

This research project is designed to utilize primarily the rawinsonde and satellite data from COARE. The PIs participated in planning sessions for the rawinsonde array. Dr. McBride obtained funds from an Australian agency to provide the full support for one of the rawinsonde stations.

Both PIs visited the field site in Townsville during COARE, but most of their efforts during the experiment were in Melbourne. Mr. Houjun Wang, a PhD student working with the PIs, spent three months in Melbourne during the field phase of COARE processing rawinsonde data and developing analysis routines. Dr. Frank spent three weeks in Townsville and Melbourne working on this aspect of the program as well. Mr. Wang is now analyzing the data as the main thrust of his dissertation work at Penn State.

3.2 Research Results During Year 2

3.2.1 Data Processing and Methodology

The PIs have combined the available data sources into a highly useful data set for examining the large-scale flow in the COARE region. The official TOGA COARE data set may not be released until roughly 1995, but by using quick-look data from NCAR (National Center for Atmospheric Research) and BMRC Bureau of Meteorology Research Centre, Melbourne Australia), and performing statistical error-checking tests, a good rawinsonde data set was obtained. Satellite measurements of high cloud amount and mean cloud top temperature were obtained from BMRC.

The basic procedure was to track down missing surface and rawinsonde data from original sources wherever possible. The data were then subjected to screening procedures that automatically flagged measurements with that differed from the mean by more than appropriate threshold amounts. Finally, time-height cross sections of the data were printed out at each station and visually screened for obvious discrepancies.

It was decided to compute budget analyses for the seven arrays and sub-arrays shown in Fig. 1. Following procedures that proved to work well for GATE (GARP Atlantic Tropical Experiment) analyses, we filled in missing data points using a two-dimensional spatial fitting scheme. To minimize the effects of missing data points and to filter out diurnal signals and measurement errors, the data at each station were averaged for each day, and all computations were done with daily-averaged data. Some limited vertical interpolation of missing data was also performed. The success rate of data acquisition was fairly high during COARE, so it was possible to fill in a complete data set (all points present in the time-space array) using this procedure.

The data at each level and time with the completed data set are now being analyzed as outlined in the original proposal. Budgets are being computed by applying the line integral technique described by Molinari and Skubis (1988) to each array. Early results are described in the next section.

3.2.2 Large-Scale Budgets

A major goal of the work is to determine the amount and vertical distribution of heating that occurs in the COARE region. While this work is still at an early stage, preliminary results are very encouraging. The following tasks have been completed for each of the seven arrays:

1. Heat and moisture budgets have been completed for each of the seven array combinations for each day over the four month period of the intensive observation period (Nov. 1992-Mar. 1993).

2. Vertical profiles of subgrid-scale heating (Q_1) and moistening (Q_2) as defined by Yanai et al. (1973) were computed.

3. Surface fluxes of sensible heat and moisture were computed using bulk aerodynamic formulations at each of the stations and averaged over the arrays.

4. Correlations between the budget-derived rainfall, satellite rainfall proxies (high cloud amount and mean cloud top temperature) and a variety of atmospheric fields were computed.

5. Lag correlations have been performed between the convection/rainfall estimates and surface flux estimates as well as other quantities to determine whether cause and effect relationships can be determined between rainfall and parameters such as surface heat and moisture fluxes.

6. A preliminary synoptic climatology of the COARE domain has been performed, and specific weather regimes (such as westerly wind bursts, active/inactive periods) have been identified for further study.

3.2.3 Preliminary Results

While results have been computed for all seven arrays, this report will focus on the large, hexagonal region referred to as the OSA (Outer Sounding Array) and shown in Fig. 1. These results are intended to be illustrative of the types of analyses being performed at this early stage, and therefore are brief. The vertical distribution of Q_1, the budget-derived subgrid-scale heating, is shown in Fig. 2 averaged over 30 day intervals corresponding approximately to the four calendar months of the IOP (Intensive Observational Period) of COARE, as well as for the 120 day average of the entire IOP. While the 120-day mean profile resembles that of other tropical maritime studies, considerable month to month variability can be seen over even this large array. Not only does the magnitude of the diagnosed diabatic heating vary dramatically between months, the vertical distribution varies markedly as well. During February, the level of maximum heating averaged near 700 mb, while during the other months the heating is maximum near 400 mb. Variations in the magnitude and vertical distribution of diabatic heating are of the same relative magnitudes (though sometimes with different patterns) in the other six arrays.

As noted by Frank and McBride (1989), heating concentrated in the lower troposphere was characteristic of convective systems in the E. Atlantic during GATE. They also showed that AMEX systems tended to have maximum heating in the middle troposphere, near 500 mb. The large scale of the COARE rawinsonde array and the variability of the heating profiles in time and space should allow considerable progress to be made in understanding the mechanisms govern the distribution of heating.

Computations of vertically integrated budgets were averaged over each month and for the entire IOP, and the results are shown in Table 1. In these computation, no radiation data were available. Therefore, rainfall was estimated from the moisture budgets, and by subtracting this budget-rainfall from the integrated Q_1 values, estimates of radiation were obtained as residuals. One major motivation for doing this was to check the reliability of the long-term budgets. Although detailed radiative heating computations for the COARE region will not be available for another year or more, the vertically integrated values are expected to be similar to those from other tropical maritime regions. The residual radiation values for the seven arrays of this study, when averaged over the entire IOP, ranged only from about -0.90 to -1.45 C/day, which compares very well with the -1.1 to -1.2 C/day for GATE, as discussed by Frank (1980). The values for individual months were generally similar. Thus, the results indicate that the critical divergences and surface fluxes for the arrays are being computed to a good level of accuracy (within a few tenths of a degree per day through the vertical column) when averaged over period of a month or more. We are investigating the accuracy at shorter (individual day) time periods using this and several other techniques, such as computing the mass-balance errors in the kinematic divergence fields. The analyses appear to be quite good in all arrays.

One of the major goals of TOGA COARE was to get a more accurate estimate of the surface to air energy fluxes in the equatorial western Pacific region. The time-averaged budgets indicate that the values computed by daily station-by-station estimates of sensible and latent heat fluxes using bulk aerodynamic formulae are likely to be accurate within +/- 20% or so. For the OSA, the mean energy flux is estimated as about 205 W/m^2, somewhat larger than was anticipated. Computations for the IFA are essentially identical.

Fig. 3 shows time series of the vertically integrated Q_1 and Q_2 (apparent moisture sink, as in Yanai et al., 1973) for the OSA. Also shown is a time series of $Q_1 - Q_2$, which should equal the sum of the surface energy flux plus the radiative cooling. The data have been smoothed slightly with a 5-day polynomial. The radiation values are not expected to vary more than a small amount from day to day, so variations in the $Q_1 - Q_2$ curve reflect an estimate of the variations in the surface fluxes of sensible heat plus moisture, primarily the latter. Interestingly, the fluxes are highest during periods of convective activity. We have performed correlations and lag correlations between these and other variables. It is clear that the surface fluxes are strongest during and after convection, but there is no clear signal suggesting that the fluxes precede the convection. This is and important point that we are investigating further.

Results to date show an interesting degree of consistency between cases. Each day was classified into one of five categories based on the vertically integrated value of Q_1. The highest category was for values above 4.5 C/day, roughly equivalent to an area-averaged rainfall rate of 1.8 cm/day. In the case of the OSA, 15 of the 120 days fell into this strong precipitation category, and the vertical profiles of Q_1 for each of these days is shown in Fig. 4. The similarities are quite striking. It is clear that the heating profile during periods of strong heating occurs with a characteristic vertical distribution. However, the vertical distribution is different at different rainfall rates and for different geographical regions. The reasons for these differences will be explored during the third year of the project.

3.2.4 TCM90

In addition to the main thrust of the research, one M.S. student (Mr. Timothy Marchok) has continued to analyze data from the TCM90 experiment, studying the relationships between tropical cyclone intensity and upper-level large-scale circulation patterns. He is expected to complete his study during the Fall 1993 semester.

4. Third Year Plans

The work for year three will continue to follow the plan laid out in the proposal fairly closely. As noted in the first annual report, we will be performing EOF analyses of the vertical heating profiles in conjunction with Dr. George Young of Penn State to break down the heating into various component mechanisms. This will facilitate quantitative comparisons with heating profiles from other tropical data sets. The technique is similar to that of Alexander et al. (1993). We will be extensively analyzing that relationships between large-scale circulation features and the variations in surface fluxes and heating amounts and distributions. The work on tropical cyclone intensity change using TCM90 data will be completed. The modelling studies of vertical structure using the COARE data should begin early in the third year, and significant results should be in hand by the scheduled completion of the project.

5. Changes in the Work Plan

No significant changes in the work plan are anticipated.

6. References

Alexander, G.D. G.S. Young and D.V. Ledvina, 1993: Principal component analysis of vertical profiles of Q_1 and Q_3 in the tropics. Mon. Wea. Rev., 121, 535-548.

Frank, W.M. (1980): Modulations of the net tropospheric temperature during GATE. J. Atmos. Sci., 37, 1056-1064.

Frank, W.M. and J.L. McBride, 1989: The vertical distribution of heating in AMEX and GATE convective systems. J. Atmos. Sci., 46, 3464-3478.

Molinari, J. and S. Skubis, 1988: Calculation of consistent flux and advective terms from adjusted vertical profiles of divergence. Mon. Wea. Rev., 116, 1829-1837.

Yanai, M., S. Esbensen and J.H. Chu, 1973: Determination of bulk properties of tropical cloud clusters from large-scale heat and moisture budgets. J. Atmos. Sci., 30, 611-627.

TABLE 1

	Q_1	Q_2	S_o	LE_o	Q_R	P_q
OSA	2.1	1.5	0.2	1.7	-1.4	3.3
OSA-S	2.2	1.5	0.2	1.7	-1.2	3.2
OSA-N	1.9	1.5	0.1	1.2	-0.9	2.6
IFA	2.0	1.6	0.1	1.7	-1.5	3.4
PNG	0.7	0.4	0.2	1.0	-0.9	1.4
PNG-N	1.1	0.9	0.1	1.2	-1.2	2.1
LSA	1.3	1.0	0.2	1.2	-1.0	2.1

120-day averages of heating terms, expressed as equivalent warming of the sfc - 100 mb column (C/day).

Q_1 = apparent heat source, Q_2 = apparent moisture sink
S_o = surface sensible heat flux, LE_o = surface latent heat flux
P_q = estimated rainfall from moisture budget, Q_R = radiative heating (residual).
(Note: $Q_R = Q_1 - P_q + S_o$).

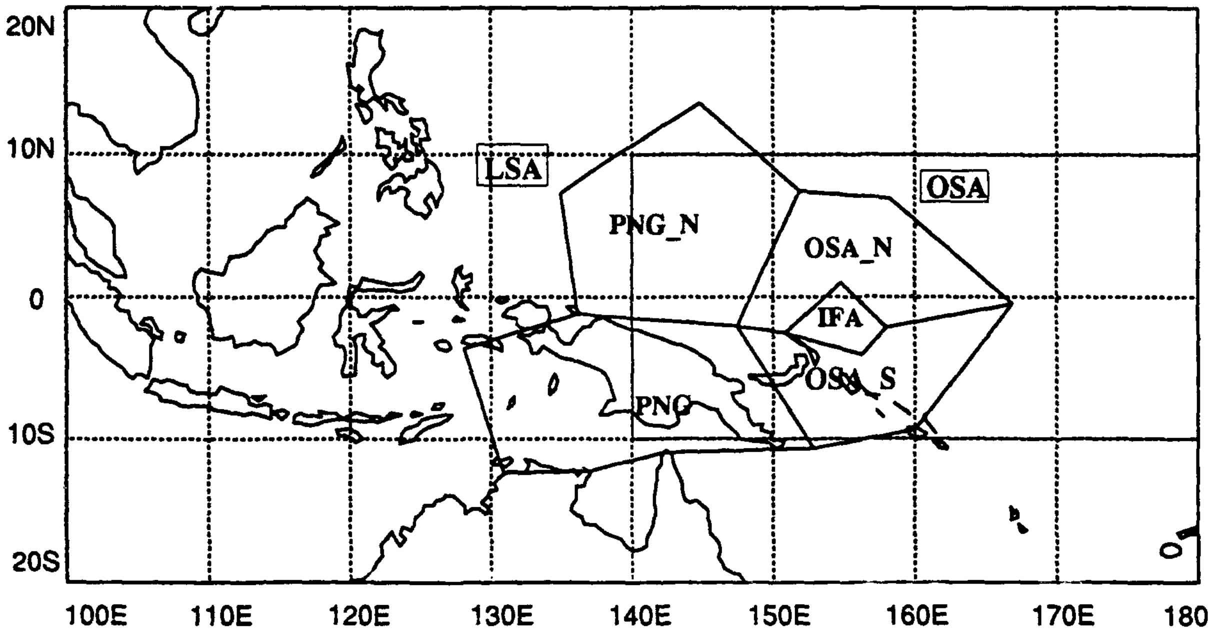

Fig. 1 Data array for this study. Rawinsonde stations are at the points of the polygons. OSA is the large hexagon to the east that is further divided into OSA-N and OSA-S subarrays. The IFA is in the center. LSA refers to the entire region contained within the polygons.

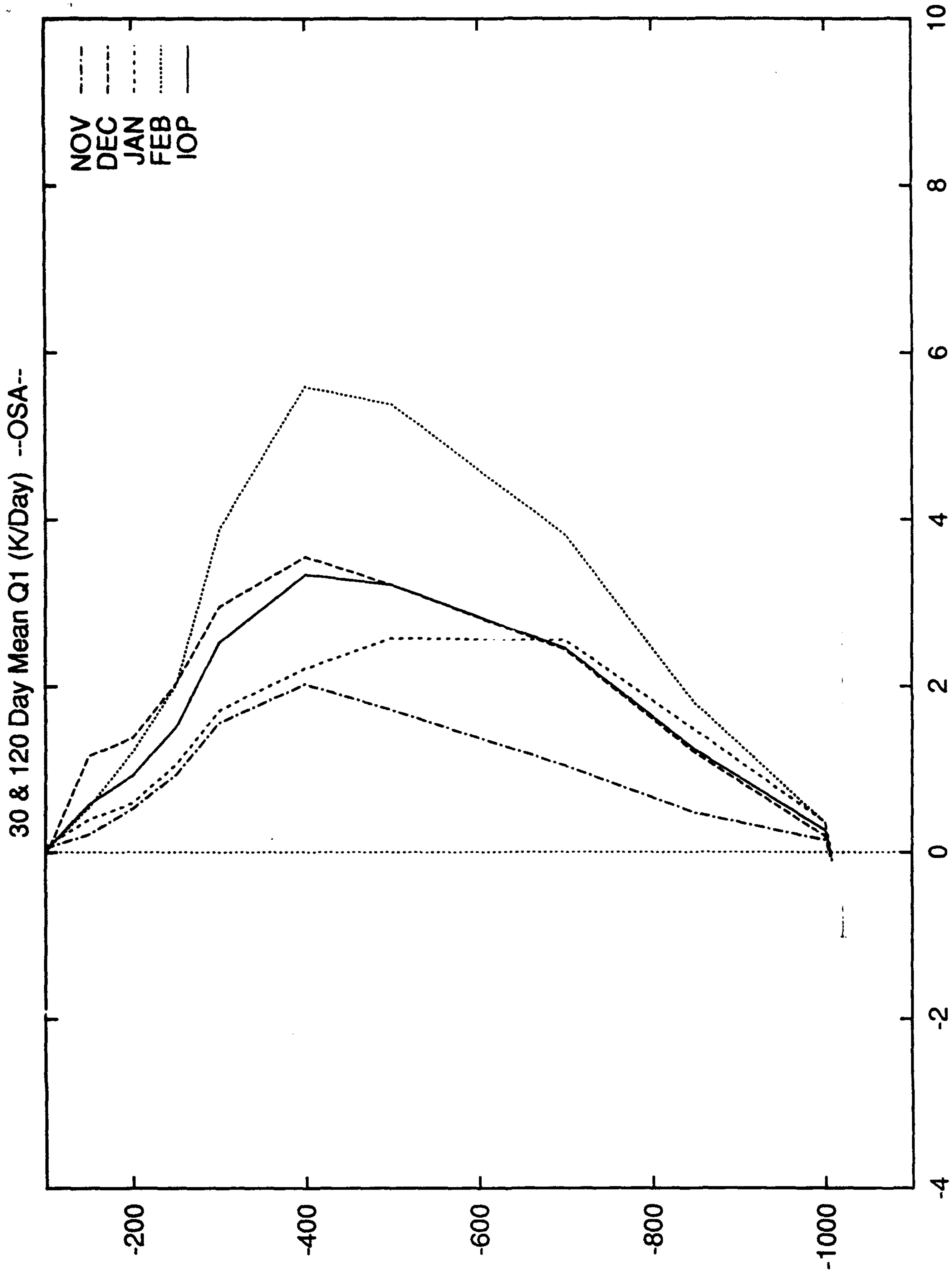

Fig. 2 Vertical heating profiles for the OSA for individual months and for the entire 120-day IOP. (C/day)

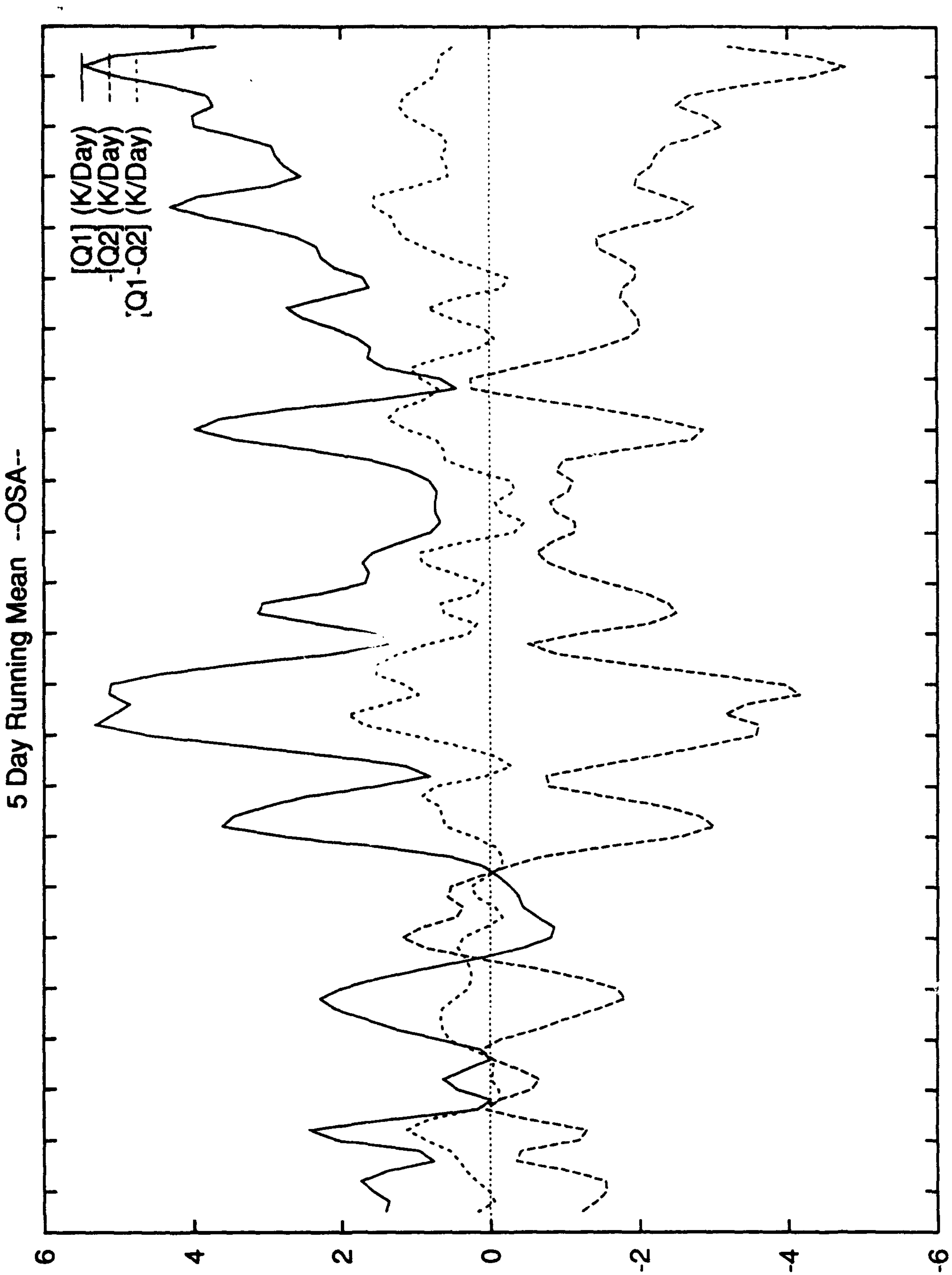

Fig 3. Time series of vertically integrated Q_1, Q_2 and Q_1 - Q_2. (C/day)

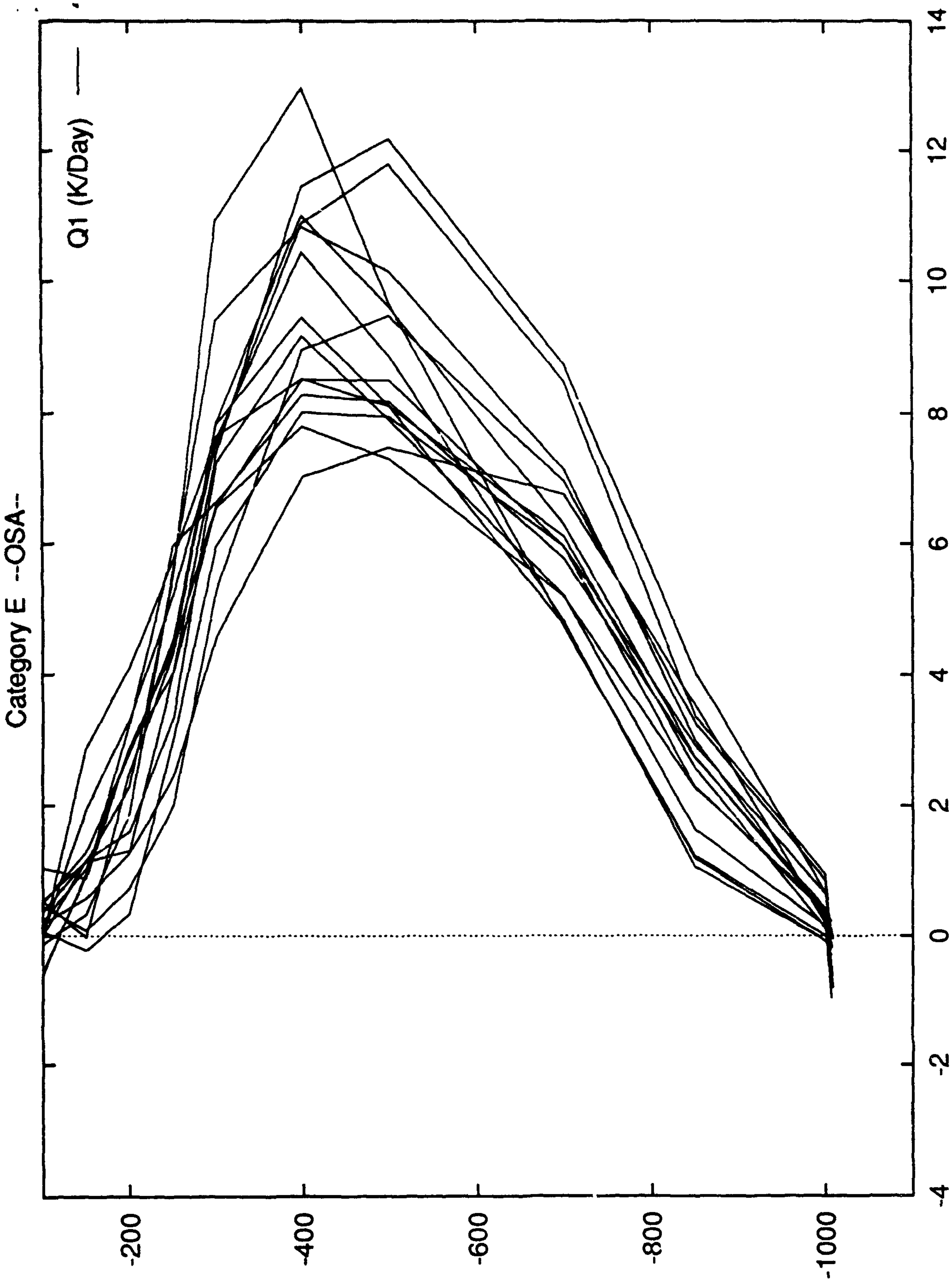

Fig 4. Vertical profiles of Q_1 for 15 individual days with vertically integrated heating greater than 4.5 C/day. (C/day)